NBS REPORT

7227

SITING FACTORS FOR VORTAC

PART I

VOR SITING

by

R. S. Kirby and L. G. Hause

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
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ABSTRACT

Modifications in siting criteria are suggested for the VHF Omni-Directional Range navigation aid. Specifically, changes of transmitting antenna height and vertical pattern shape which would decrease undesired ground reflections and increase the range of service are proposed. A short discussion of azimuth errors due to undesired reflections is presented. A method of optimizing the angle of tilt for a given vertical pattern and antenna height is presented. Finally, the results of calculated expected coverage patterns for two tilted arrays and a typical VOR transmitting antenna are compared.

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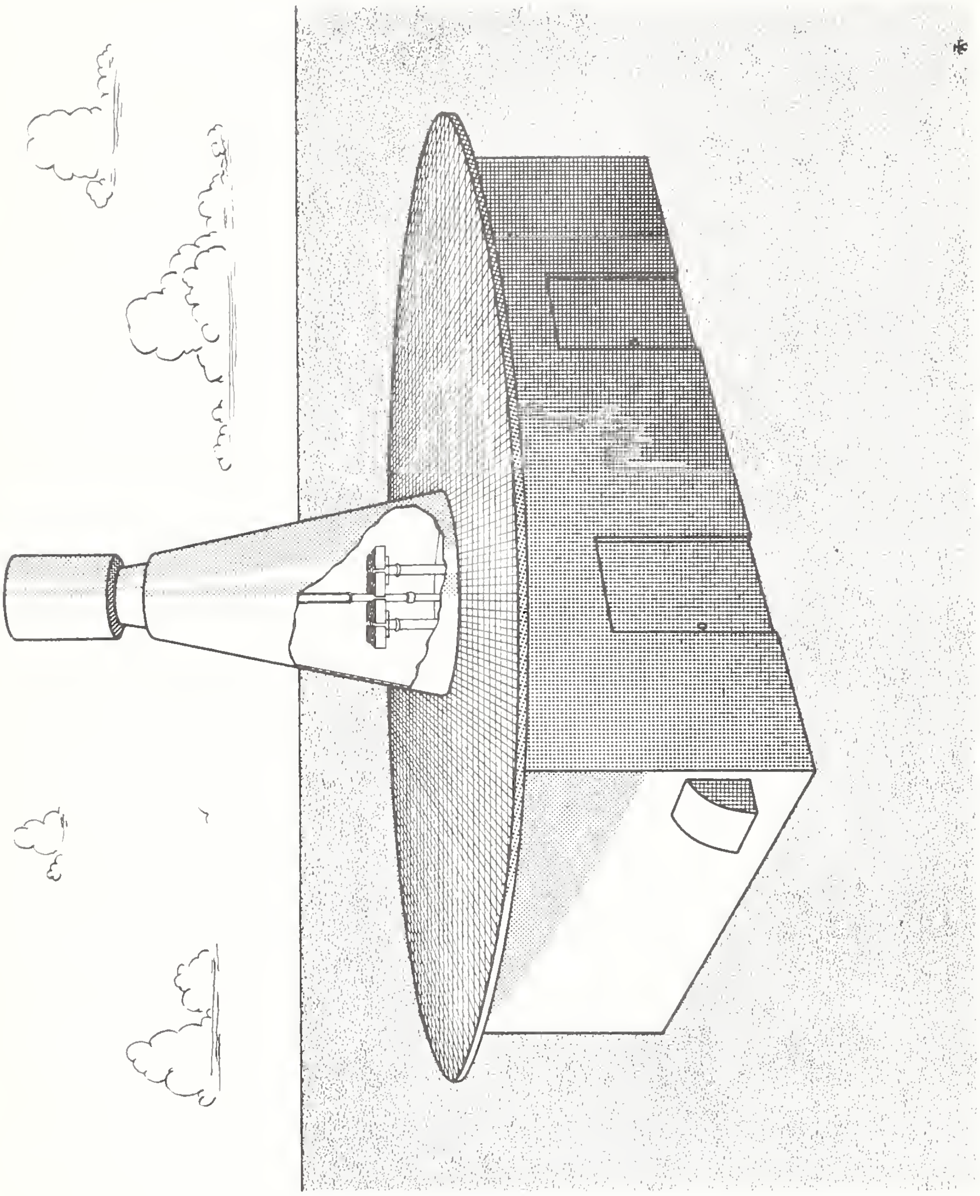
1. INTRODUCTION

The VHF Omni Range (VOR) operates on sixty 100 kc/s channels in the frequency band 112.0 - 118.0 Mc/s. It provides to aircraft visual course-line information toward or away from the station at any azimuth throughout service volumes extending nominally 200 statute miles from the ground station using 200 watts of transmitter power.

Briefly the theory of operation is as follows: A 30 c/s space modulated signal is transmitted by a revolving figure-eight pattern radiated from a four-loop array. The phase of the 30 c/s space modulation is compared with a reference 30 c/s FM modulated signal to indicate azimuth in the airborne unit. Figure 1 shows a drawing of a standard four-loop array currently in use.

The present VOR antenna configuration employs a four-loop array of horizontally-polarized loop antennas mounted about four feet above a counterpoise. The purpose of the counterpoise is to prevent the formation of lobes caused by interference between direct and ground-reflected rays. Even with the counterpoise, significant ground reflections occur at low elevation angles where most of the first Fresnel zone falls on the ground beyond the counterpoise. So long as the elevation of the counterpoise is kept less than roughly eighteen feet only the lowest part of the first lobe is formed, and no serious nulls can develop. If the counterpoise were raised to higher elevations more and finer lobes could be formed, and nulls would occur in the low angle coverage. This factor places a severe restriction on VOR siting using the counterpoise in the presence of obstacles, because in these areas sufficient elevation is needed not only to clear the obstacles but also so as not to illuminate them with RF energy. Thus some other method of eliminating lobes would be preferable if it would allow the use of higher antenna elevations.



A TYPICAL VORTAC INSTALLATION

FIGURE I

The VOR system is susceptible to many sources of error the majority of which are the result of off-path reflections from natural or man-made terrain features; buildings, fences, power lines, etc.

These errors in azimuth indication arise from reflections off the path which produce a signal not in phase with the desired space modulation at the aircraft. Only a small amount of energy need be reflected in order to cause serious errors in indicated azimuth. Figure 2 shows the expected error in phase, and consequently azimuth indication, of the space modulated signal as a function of the voltage ratio A_2/A_1, where A_1 represents the direct signal and A_2 the signal reflected to the aircraft from a single reflector off the path. It can be seen from Figure 2 that when the reflecting object is at an azimuth 80° to 120° from the aircraft azimuth errors in excess of 2.5° can occur when $A_2/A_1 > 0.05$.

The Flight Inspection Manual [1956] defines a number of this type of error as follows:

Course Bends. Slow excursions of the course.

Course Roughness. Rapid irregular excursions of the course.

Course Scalloping. Rhythmic excursions of the course.

Polarization Effect. Inconsistent course deviation indications with aircraft altitude changes caused by the existence of undesired polarization.

Some efforts have been made to minimize siting problems in difficult areas through the use of elevated antennas. Anderson and Flint [1960] reported on tests using a 200-foot tower with a 60-foot diameter counterpoise. This antenna was erected in a heavily wooded area where course errors for a low, portable VOR located in the same 200-foot square cleared area were found to be as much as plus or minus 11.5°. Using the tower-mounted antenna most of the course errors were within tolerance. The worst errors occurred at heights corresponding to the first null in the vertical radiation pattern where a maximum scalloping error of ±6° was observed. It was concluded that the most serious scalloping occurred when the aircraft was located in nulls below about 7° in elevation and in particular along radials over smooth, clear terrain which made specular reflection possible. This error is probably due for the most part to the fact

EXPECTED AZIMUTH ERROR FROM A SINGLE OFF-PATH REFLECTION AS A FUNCTION OF THE RELATIVE STRENGTH OF THE DESIRED SIGNAL, A_1, AND THE REFLECTED SIGNAL, A_2

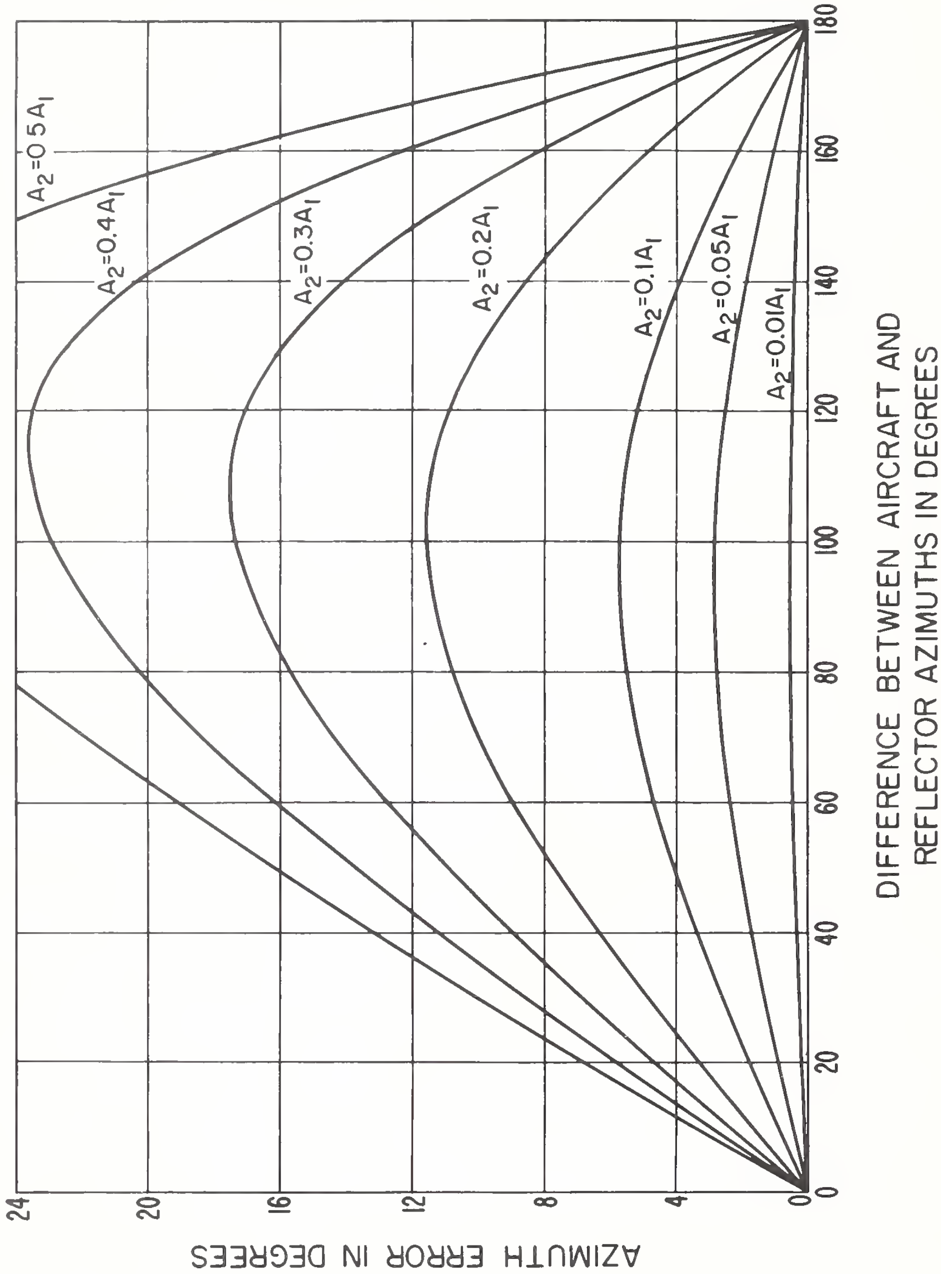


Figure 2

that the aircraft is in a narrow zone of relatively weak fields where it is much more susceptible to reflections from off the path than when in other locations.

From a consideration of the geometry in terms of a reflecting area first Fresnel zone, the counterpoise reflects only a small part of the ground-reflected energy at low elevation angles. Most of the ground-reflected energy is reflected from the surrounding terrain. As the counterpoise is currently used this presents no problem. However, if the entire antenna including the counterpoise were raised, serious lobing at these low elevation angles would likely occur. The surrounding terrain can be quite rough and still give rise to a specular reflection and thus to pronounced lobing if it meets the Rayleigh criterion of roughness illustrated in Figure 3. For example, if an aircraft is at 100 nautical miles at an altitude of 10,000 feet, $\psi \cong 0.4^\circ$. It follows that at 115 Mc/s (λ = 3.5 meters) Δh must be less than about 80 feet for specular reflection.

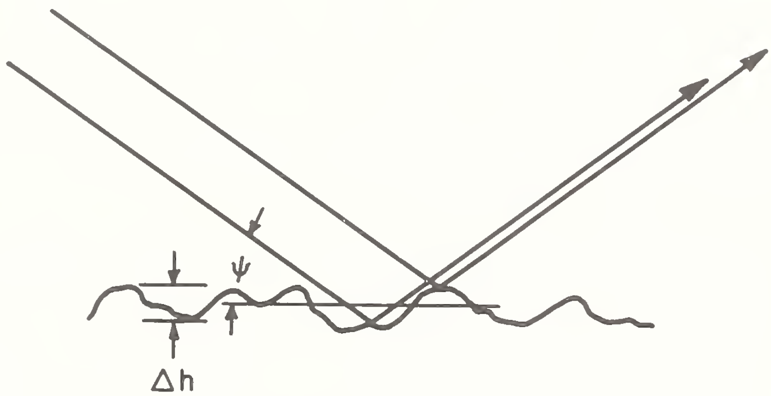


Figure 3. Rayleigh's Criterion of Roughness for Specular Reflection

$$\Delta h < \frac{\lambda}{16 \sin \psi}$$

The preceding factors suggest another approach to the use of antennas at higher elevations above the terrain. It is well known that a high-gain antenna with a narrow vertical radiation pattern, tilted up in all azimuthal directions, can be employed to minimize ground reflection effects. For example, see Kirby, Herbstreit, and Norton [1952]. The current study is an analysis of the expected coverage and

of the lobe structure for a VOR system using a vertical collinear array of horizontal elements phased electrically to obtain an optimum angle of tilt. Methods are considered for optimizing the height of the array above ground in terms of the resulting vertical lobe pattern.

On the basis of estimated structural costs furnished by the Federal Aviation Agency of $35, 000 for the conventional VOR and $55, 000 for the doppler VOR, costs for a tilted array facility would be of about the same order or possibly less than that of a conventional VOR. Additional savings would result in being able to use adverse sites with minimum preparation.

2. THEORY OF OPERATION

The RF energy received by an aircraft within the line of sight from a transmitter on the ground can be considered to have two primary components, the direct wave and the ground-reflected wave. The direct wave corresponds to a free-space wave while the ground-reflected wave travels over a somewhat longer path and suffers some attenuation upon being reflected from the ground. It also undergoes a shift in phase which for horizontal polarization equals approximately 180°. In general, there are two lobes in the vertical coverage pattern for every wavelength in height of the ground antenna. Figure 4 shows a coverage pattern for a uniformly radiating (isotropic) antenna, horizontally polarized over smooth spherical earth.

To compute the coverage expected in a ground-air radio transmission link it is necessary to consider the phase relations and magnitudes of the two components. This can be accomplished under the assumption of a finitely-conducting, smooth, spherical earth as representative of the terrain. This assumption usually tends to be somewhat pessimistic in terms of nulls in the lobe pattern but is reasonably valid at low elevation angles where specular reflection frequently occurs.

The usual assumptions for VOR are as follows:

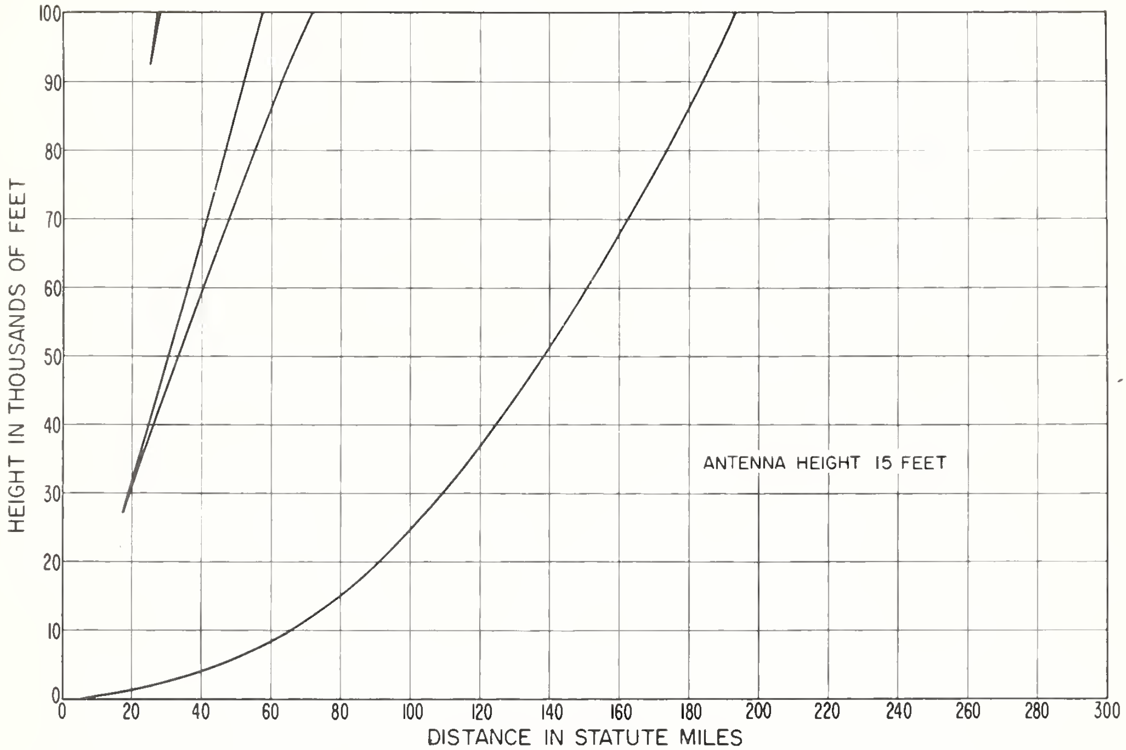
Transmitter power, $p_t = 200$ watts.

Minimum receiver terminal voltage across 50 ohms = $5 \mu V$.

It follows that the required power to be delivered to the receiver is 5×10^{-13} watts. Allowing 6 db for line, mismatch, and other non

VOLTAGE COVERAGE PATTERNS FOR AN ISOTROPIC ANTENNA
ABOVE A SMOOTH SPHERICAL EARTH

FREQUENCY 115 Mc/s POWER 200 WATTS
CONTOUR 50 μV HORIZONTAL POLARIZATION



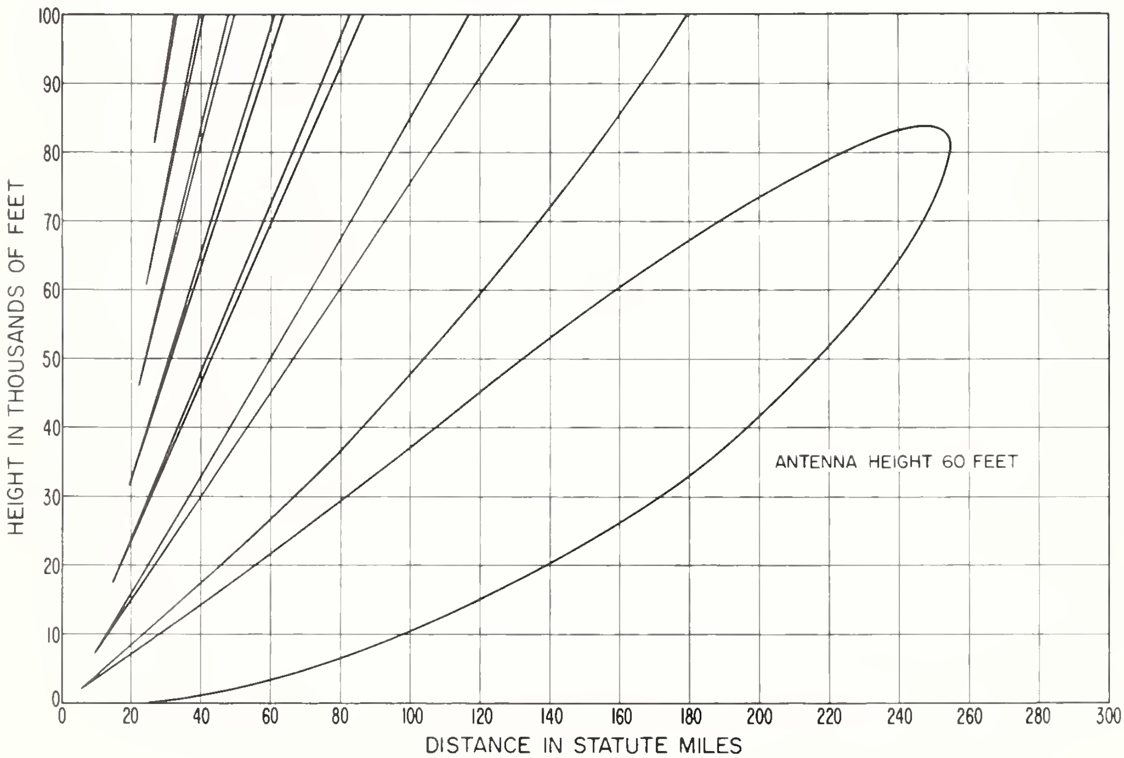


Figure 4

propagation losses, the system loss defined as $L_s \equiv 10 \log_{10} p_t/p_a$ is equal to 140 db. Basic transmission loss, L_b, is used to separate the effects of transmitting and receiving antenna gain and circuit losses from the effects of propagation, $L_b = L_s + G_{pp}$. This involves the concept of path antenna power gain, G_{pp}, which is the sum of the realized gains of transmitting and receiving antennas expressed in db, including the effects of circuit losses. The path antenna power gain is the change in system loss when loss-less isotropic antennas are used at the same locations as the actual antennas.

In free space basic transmission loss, L_{bf}, varies with frequency and distance as follows:

$$L_{bf} = 36.581 + 20 \log f_{mc} + 20 \log d_{stat\ mi} \text{ db} \tag{1}$$

For a within-the-horizon path the ground-reflected energy must be included. This can be considered to be a vector ray which is attenuated by a ground reflection coefficient, R, at a phase angle designated $\pi - c$ relative to the incident ray. For horizontal polarization, c is a small negative angle. In addition to the reflection coefficient there is additional attenuation due to the spreading of the energy reflected from a convex earth which is accounted for by a divergence factor D. The law of cosines can be used to find the resultant magnitude of the electric vector made up of the direct, free-space wave and the ground-reflected wave in terms of basic transmission loss, L_b.

$$L_b = L_{bf} + 10 \log \left[1 + (DR)^2 - 2DR \cos (\Delta_r - c) \right] \text{ db} \tag{2}$$

In (2) the geometry of Figure 5 is referred to.

$$D = \left[1 + \frac{2d_1 d_2}{a\ d \tan \psi} \right]^{-\frac{1}{2}} \tag{3}$$

[(3) is valid when $2d_1 d_2/(a\ d \tan \psi) < 0.016$.]

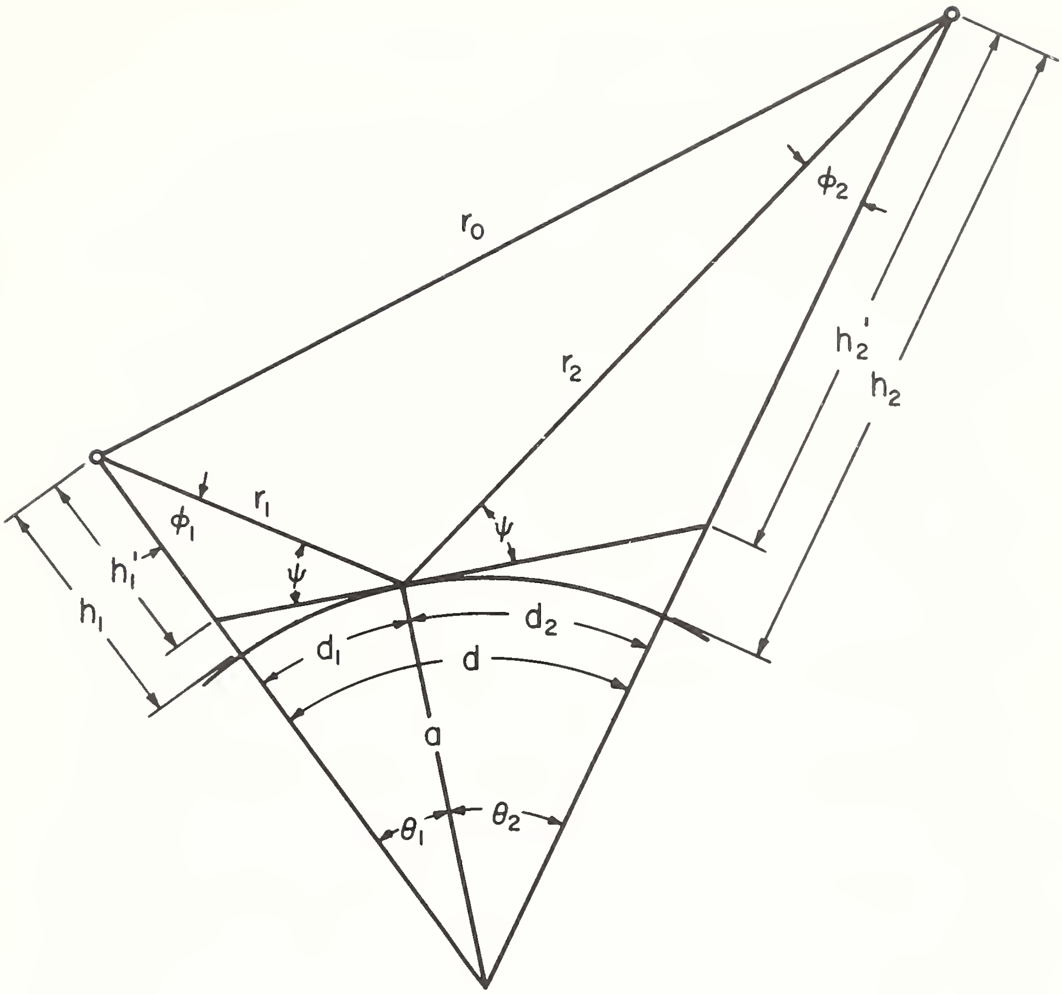


Figure 5. Geometry for Within-the-Horizon Propagation Over a Spherical Earth

For horizontal polarized waves

$$R = |R| e^{i(\pi - c)} = \frac{\sin \psi - \sqrt{n^2 - \cos^2 \psi}}{\sin \psi + \sqrt{n^2 - \cos^2 \psi}} \qquad (4)$$

$n^2 = \epsilon - ix$, $x = 60\sigma\lambda$, ϵ is the relative dielectric constant and σ the conductivity of the ground in mhos/m.

The geometric path length difference in radians,

$$\Delta_r = \frac{2\pi}{\lambda}\left(r_2 + r_1\right)\left\{1 - \sqrt{1 - \frac{4r_1 r_2 \sin^2 \psi}{(r_1 + r_2)^2}}\right\} \tag{5a}$$

For small elevation angles, the following equation is sufficient:

$$\Delta_r = \frac{4\pi\, h_1'\, h_2'}{\lambda d} \quad \text{radians} \tag{5b}$$

or more conveniently with h_1', h_2' in feet and d in statute miles

$$\Delta_r = (1.38643)(10^{-4})\, f_{mc}\, h_1'\, h_2'/d \quad \text{degrees} \tag{5c}$$

To include the effect of vertical antenna directivity the voltage gain factors must also be included. Figure 6 illustrates the geometry of tilted antennas. In Figure 6 g_1 and g_2 represent the voltage gain factors for the direct and ground-reflected rays, respectively, referred to the maximum voltage gain of the array as unity. Assuming that losses associated with ohmic resistances are negligible and that $G_{pp} = G_t + G_r$ db, the sum of the gain of the transmitting and receiving antennas respectively in db, and specifically that G_t represents the maximum gain of the transmitting antenna relative to an isotropic radiator, equation (2) can be modified to take the antenna gain directivity factors into account and to solve for system loss as follows:

$$L_s = L_{bf} - G_{pp} + 10 \log \left[g_1^2 + (g_2\, D|R|)^2 - 2 g_1 g_2 D|R| \cos(\Delta_r - c) \right] \tag{6}$$

Assuming that the system loss, $L_s = 140$ db, represents the maximum value for satisfactory service, the coverage of a VOR transmitter employing a tilted array can be determined from (6) using the distance relation in L_{bf} to balance the equation to 140 db.

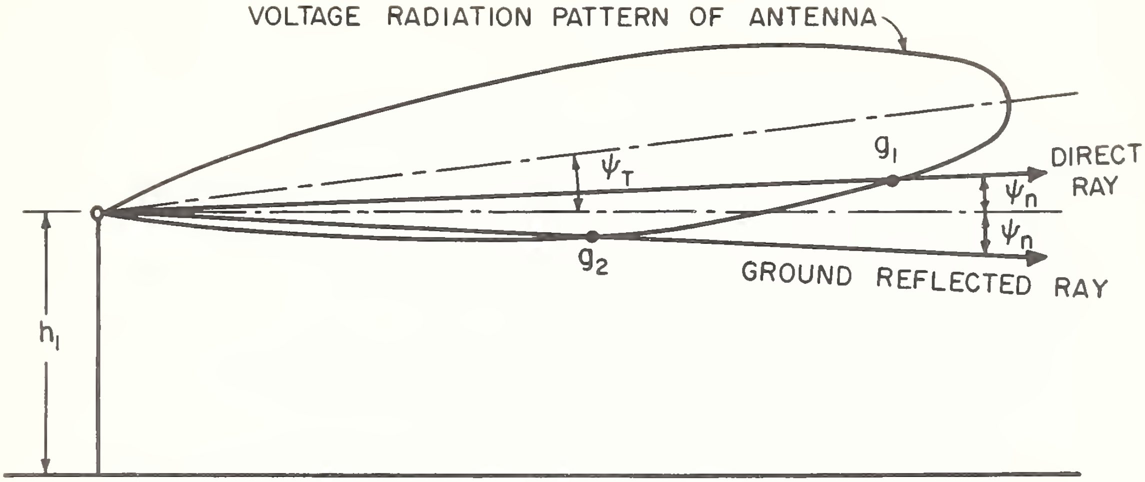


Figure 6. Suppression of Ground-Reflected Ray Obtained by Use of Height-Gain and Tilted Array

g_1 = antenna voltage gain for direct ray

g_2 = antenna voltage gain for reflected ray

ψ_T = angle of tilt for antenna pattern

ψ_n = elevation angle to null above first lobe

3. OPTIMUM DIRECTIVITY AND GROUND ANTENNA HEIGHT

The usual concept of idealized coverage for a VOR installation is considered in terms of a cylindrical service volume. If an antenna could be devised which would radiate in the presence of the ground a cosecant voltage gain pattern as shown in Figure 7, the contours of equal system loss would take the form of a cylinder in space which might be considered an ideal pattern for an air-ground service. A practical design objective in the ground antenna installation provides for no gaps in coverage within a cylindrical service volume and further that the ratios of the maxima and minima be held to a practical minimum to alleviate interference problems.

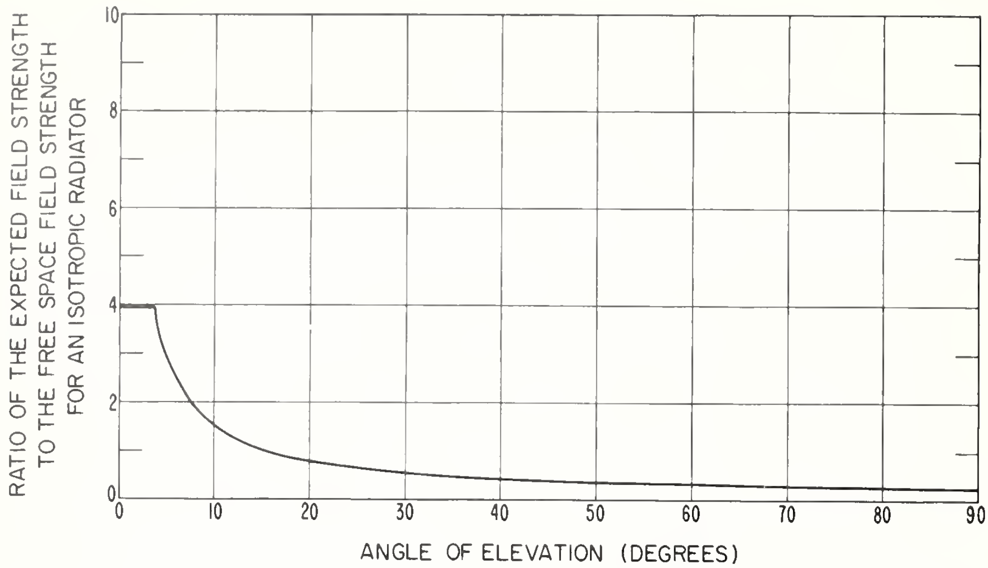


Figure 7. An Idealized Vertical Plane Field Strength Pattern for Coverage up to 70,000 Feet

The most serious gaps in the service volume are likely to occur in the nulls above the first and second lobes. When horizontal polarization is employed at VHF, the reflection coefficient near grazing incidence is approximately unity, which makes almost complete cancellation of the signal in space possible. The locations in space where this can happen can be determined from the phase relation between the direct and ground-reflected ray in equation (2) by setting $\Delta_r - c = n\ 360°$ and solving the geometry for these angles by means of equation (5). Figure 8 shows the angle of elevation from the ground transmitter to the first null as a function of the height of the ground antenna above a smooth spherical earth with an effective radius of 5280 miles (4/3's earth). As the antenna height increases the angle of elevation of the first null becomes lower. At higher antenna elevations it becomes difficult to obtain sufficient antenna pattern gain discrimination to effectively suppress the ground-reflected energy. Furthermore, too much directivity in the ground antenna is likely to result in poor high-angle coverage.

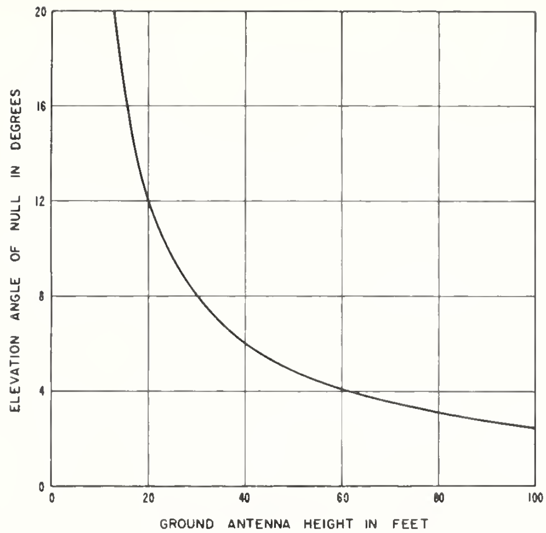


Figure 8. Elevation Angle to the Null Above the First Lobe Versus Antenna Height at 115 Mc/s Over a Smooth Spherical Earth

4. COVERAGE FOR VOR WITH ELEVATED ANTENNAS

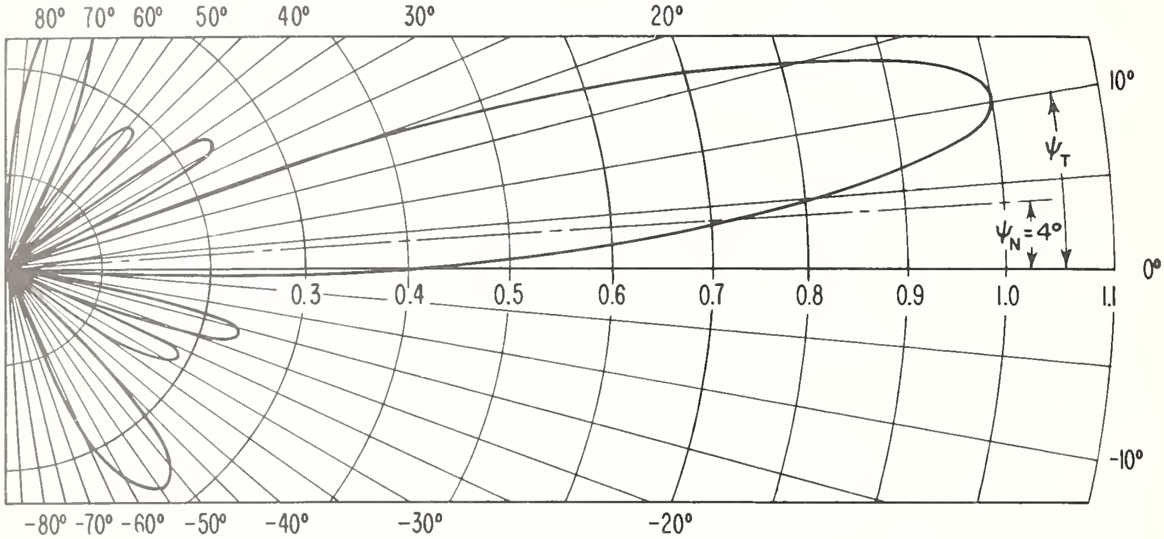
In selecting the various parameters for a high-gain, elevated VOR antenna a number of factors need to be optimized. Most factors will be influenced by the antenna directivity patterns, and it is well to select this first. If the vertical directivity is broad, problems will arise in the low elevation null; whereas if it is very narrow, high elevation coverage will suffer. Collinear arrays of four to six elements seem to provide the optimum patterns. Figure 9 shows the free-space voltage patterns for such antennas.

For any height the angle of tilt is optimized primarily for the lowest null, since it represents the most serious gap in coverage. Sometimes a compromise must be made over more than one low elevation null. Using the last term in equation (6) and setting the geometry and the reflection coefficient so that $\Delta_r - c = 360^\circ$ the ratio of field strength, E_n, in the first null to the free-space field strength in the direction of maximum gain, E_o, can be determined as follows:

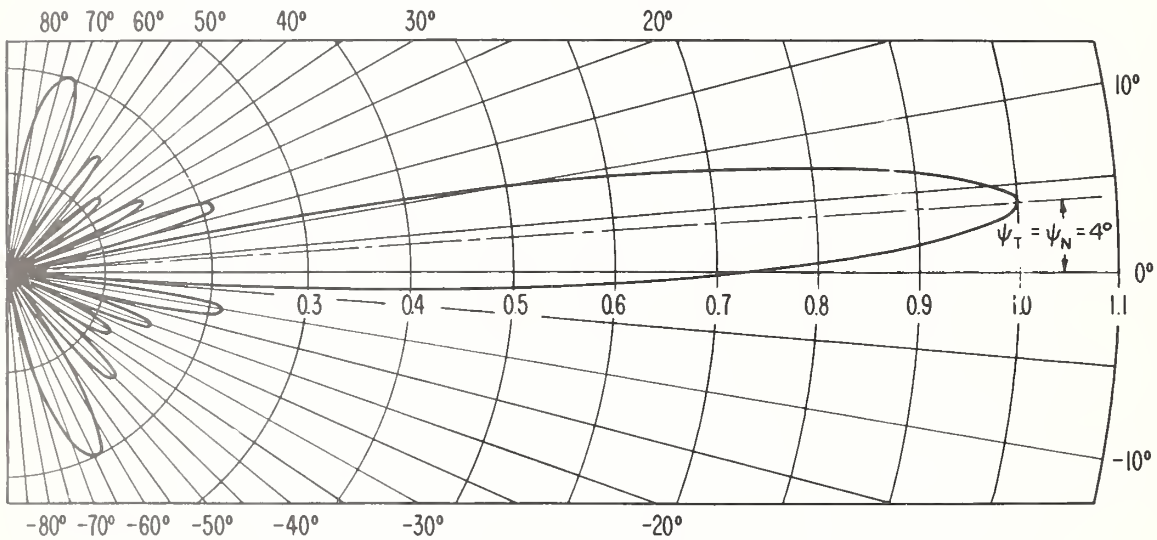
$$\frac{E_n}{E_o} = g_1 - g_2 \, DR \qquad (7)$$

THEORETICAL FREE SPACE VOLTAGE PATTERNS FOR HIGH-GAIN TILTED ARRAY VOR ANTENNA.

4 ELEMENTS $G_t = 8.5$ db



6 ELEMENTS $G_t = 10.4$ db



SPACING BETWEEN ELEMENTS 1 WAVELENGTH
HORIZONTAL POLARIZATION
ALFORD LOOP TYPE ELEMENTS

Figure 9

Figure 10 shows the variation in $g_1 - g_2$ DR as a function of the angle of tilt for both the 4-element and 6-element antennas of Figure 9. The elevation of the center of radiation is assumed to be 60 feet over a smooth spherical earth, at which height the first null for 115 Mc/s occurs at $\psi_n = 4.1°$ above the smooth earth. The height of 60 feet was chosen as a maximum practical height over smooth earth for these antennas since at higher antenna heights the first null is at too low an elevation for adequate pattern discrimination. Higher elevations can be used over rough terrain particularly in wooded areas and in mountains.

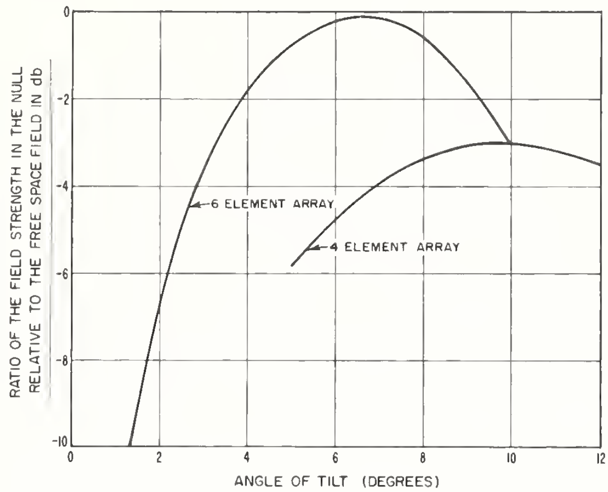


Figure 10. Relative Voltage in the Null Above the First Lobe. Antenna Patterns as Shown on Figure 9 At 60 Foot Elevation. Null Elevation 4.1 degrees at 115 Mc/s.

Line loss, and other non-propagation losses, in the system between transmitter and receiver terminals are lumped into a 6 db loss in order that the effects on coverage of propagation and antenna characteristics might be compared.

Optimum angles of tilt indicated by Figure 10 are 10° for the 4-element array and 6.6° for the 6-element array. However, this method of optimizing makes no consideration for the radiation provided on the horizon, which affects the maximum range of the system. For the more directive, 6-element array, lowering the tilt angles to approximately the elevation of the first null has only a minor effect on the radiation in the null, but does provide for adequate low-angle

radiation as can be seen in Figure 9. This is the tilt angle selected for the 6-element antenna.

Variations in the gain of the receiving antenna located on the aircraft will influence the maximum range of the system. Figure 11 shows a typical voltage gain pattern for a VOR receiving antenna consisting of an E-plane cavity located in the vertical stabilizer of the Convair 880 jet liner [Chazotte, 1959]. The value of antenna gain, G_R, used in making estimates of coverage is taken as 1.04 db relative to an isotropic antenna, and would be exceeded in 95% of the orientations of the sample pattern.

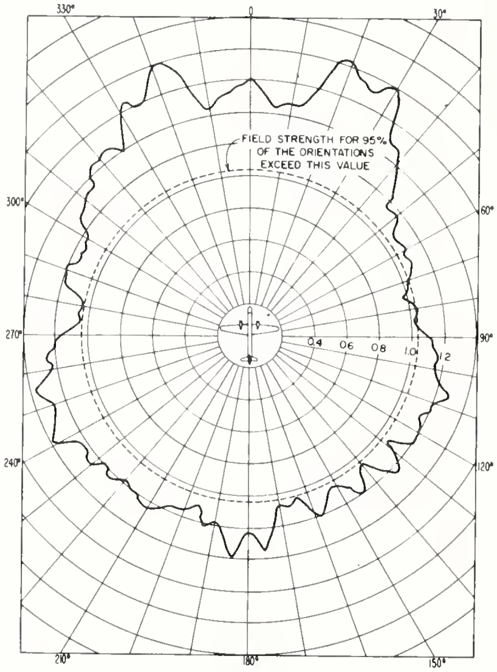


Figure 11. A Typical Aircraft E-Plane Voltage Pattern Relative to an Isotropic Radiator

Figure 12 shows typical coverage expected using the standard VOR four-loop array antenna on a 35-foot counterpoise elevated fifteen feet above a smooth spherical earth. Figure 13 shows the coverage expected under similar conditions for the 6-element array of Figure 9 at an elevation sixty feet above smooth spherical earth tilted up electrically 4° in all azimuths. Figure 14 is similar to Figure 13 except that the ground antenna is the 4-element array of Figure 9.

TYPICAL COVERAGE DIAGRAM FOR A COMMON TYPE OF VOR INSTALLATION

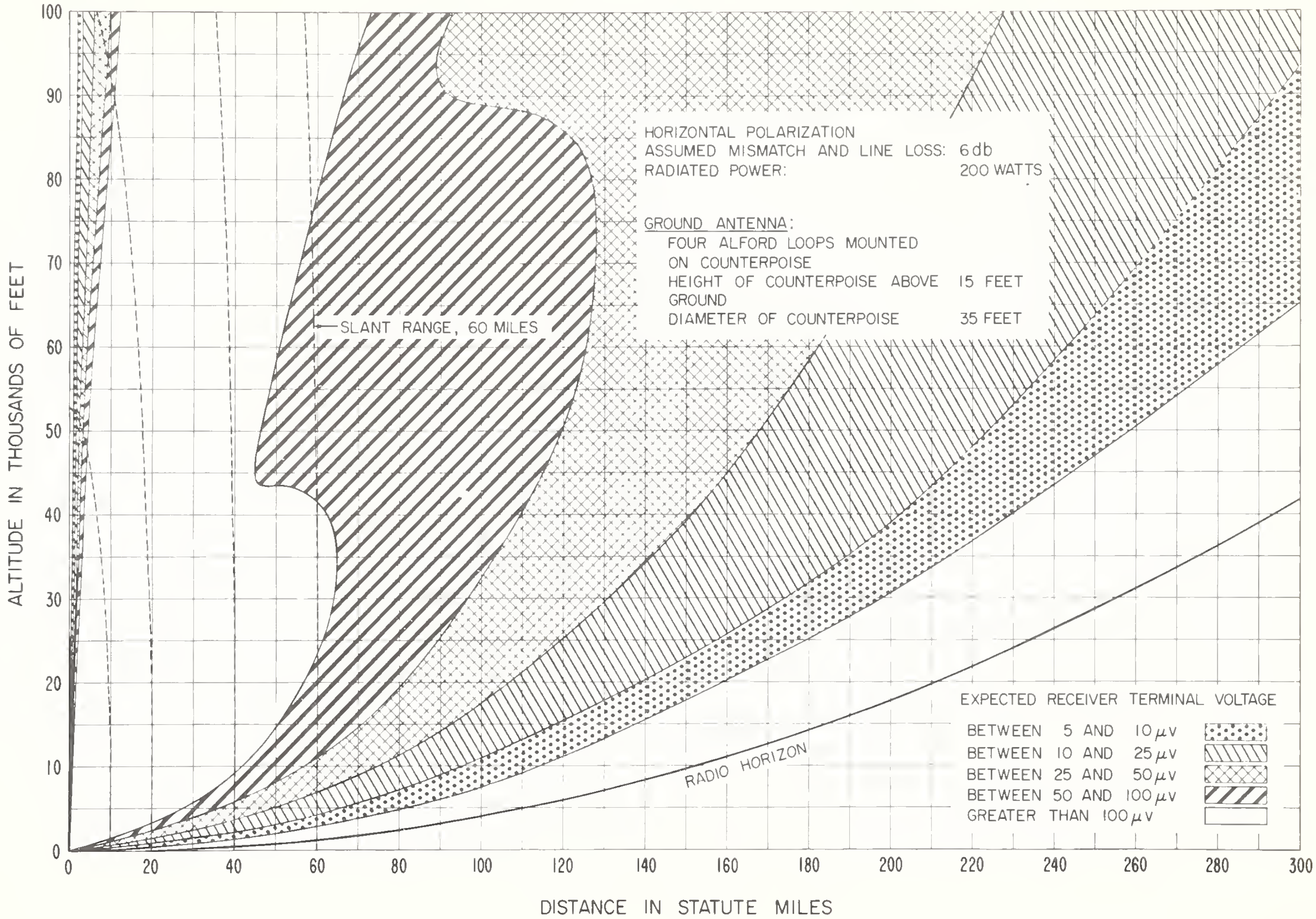


Figure 12

THEORETICAL VOR COVERAGE OVER A SMOOTH EARTH USING A SIX-ELEMENT TRANSMITTING ANTENNA ARRAY WITH ELEVATION AND TILT

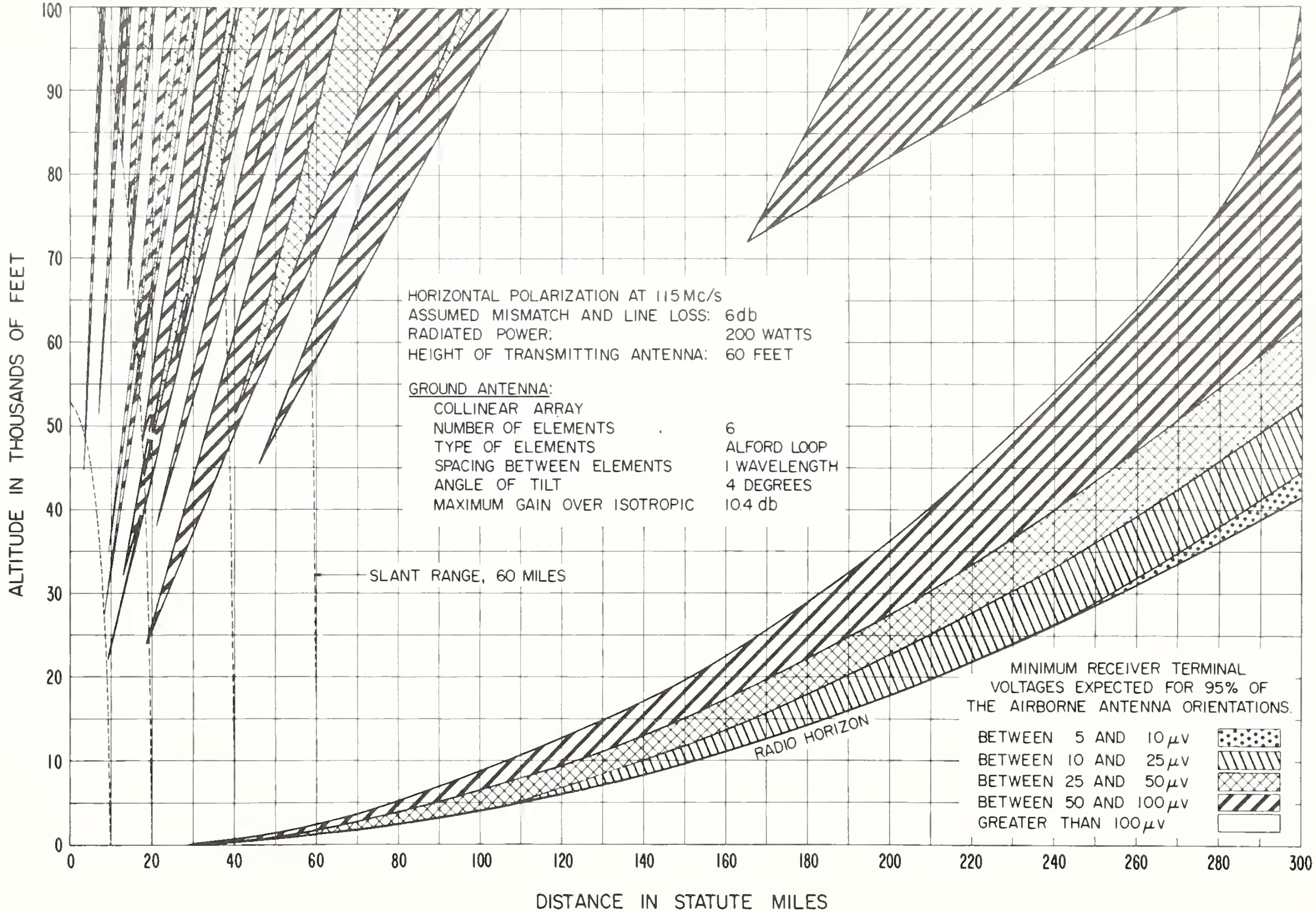


Figure 13

THEORETICAL VOR COVERAGE OVER A SMOOTH EARTH
USING A FOUR-ELEMENT TRANSMITTING ANTENNA ARRAY
WITH ELEVATION AND TILT

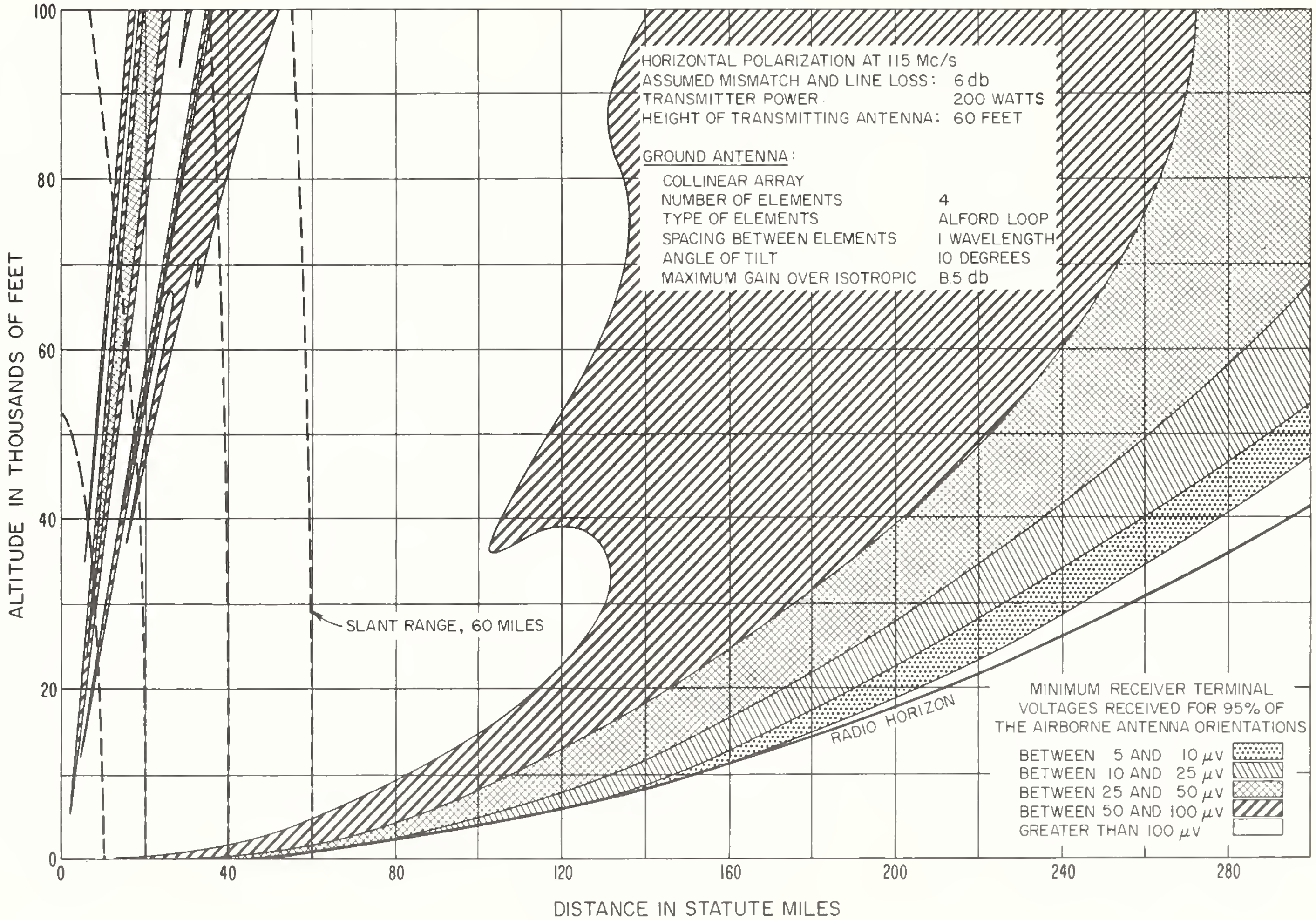


Figure 14

A comparison of Figures 12, 13, and 14 shows that the elevated high-gain antennas provide much more coverage at low elevation angles when compared to the low counterpoise antenna. At the higher aircraft elevations some lobing occurs. The latter is due in part to the absence of the counterpoise and in part to the fact that radiation in this area is through side lobes. However, at any practical aircraft altitude the slant ranges to aircraft at high elevation angles is small. With the 6-element array and an aircraft at 100,000 feet only in a few small zones at less than 40 miles would the receiver terminal voltage be expected to fall somewhat below 25μV. With the 4-element array the high elevation angle lobing is even less serious.

Consequently, the coverage in terms of available power is essentially gapless to all altitudes considered.

5. CONCLUSIONS AND RECOMMENDATIONS

A study is made of the application of elevated high-gain tilted array antennas to the VOR system. The primary concern is to provide a signal in space which is not seriously affected by off-path reflections from trees, rough terrain, buildings, etc. This type of reflection results in azimuth errors indicated in the airborne receiving equipment. In addition to alleviating the off-path reflection problems, these elevated transmitting antennas are expected to provide for considerable improvement in low angle coverage as well as to simplify site selection and preparation.

The use of the elevated antenna with tilt and vertical directivity eliminates the requirement for a counterpoise. In fact the design and physical construction of such antennas would be considerably different from and in many respects more simple than antennas currently in use. Some work has already been done in developing antennas for VOR which would be adaptable for the high-gain arrays. For example, see Alford [1954].

The lobing problems at high elevation angles need to be investigated further with some experimentation. These are expected to be most severe over smooth terrain and place an upper limit on the height of the transmitting antenna. In wooded areas and over rough terrain higher heights can be used. This in itself is a strong advantage for the elevated antenna since every effort should be made to elevate the antenna as high as possible to clear nearby reflecting terrain features.

It should never be necessary to cut down extensive growths of trees to prepare sites since all that is needed is to elevate sufficiently above them.

If there is strong interest in utilizing the techniques in this paper it is recommended that tests under various terrain conditions be performed. It will also be necessary to make determinations of the interference effects between this type of radiating system and other similar radiating systems as well as with the standard VOR systems. Most of the important aspects of such a study can be performed analytically.

Part II of this paper, which follows under separate cover, will analyze the aspects of raising the TACAN antenna to be compatible with the elevated VOR collinear array.

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Errata for NBS Report 7227

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Page 1: The first sentence should be changed to read as follows:

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U. S. DEPARTMENT OF COMMERCE
Luther H. Hodges, *Secretary*

NATIONAL BUREAU OF STANDARDS
A. V. Astin, *Director*

THE NATIONAL BUREAU OF STANDARDS

The scope of activities of the National Bureau of Standards at its major laboratories in Washington, D.C., and Boulder, Colorado, is suggested in the following listing of the divisions and sections engaged in technical work. In general, each section carries out specialized research, development, and engineering in the field indicated by its title. A brief description of the activities, and of the resultant publications, appears on the inside of the front cover.

WASHINGTON, D.C.

Electricity. Resistance and Reactance. Electrochemistry. Electrical Instruments. Magnetic Measurements. Dielectrics. High Voltage.

Metrology. Photometry and Colorimetry. Refractometry. Photographic Research. Length. Engineering Metrology. Mass and Scale. Volumetry and Densimetry.

Heat. Temperature Physics. Heat Measurements. Cryogenic Physics. Equation of State. Statistical Physics.

Radiation Physics. X-ray. Radioactivity. Radiation Theory. High Energy Radiation. Radiological Equipment. Nucleonic Instrumentation. Neutron Physics.

Analytical and Inorganic Chemistry. Pure Substances. Spectrochemistry. Solution Chemistry. Standard Reference Materials. Applied Analytical Research.

Mechanics. Sound. Pressure and Vacuum. Fluid Mechanics. Engineering Mechanics. Rheology. Combustion Controls.

Organic and Fibrous Materials. Rubber. Textiles. Paper. Leather. Testing and Specifications. Polymer Structure. Plastics. Dental Research.

Metallurgy. Thermal Metallurgy. Chemical Metallurgy. Mechanical Metallurgy. Corrosion. Metal Physics. Electrolysis and Metal Deposition.

Mineral Products. Engineering Ceramics. Glass. Refractories. Enameled Metals. Crystal Growth. Physical Properties. Constitution and Microstructure.

Building Research. Structural Engineering. Fire Research. Mechanical Systems. Organic Building Materials. Codes and Safety Standards. Heat Transfer. Inorganic Building Materials.

Applied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics. Operations Research.

Data Processing Systems. Components and Techniques. Computer Technology. Measurements Automation. Engineering Applications. Systems Analysis.

Atomic Physics. Spectroscopy. Infrared Spectroscopy. Solid State Physics. Electron Physics. Atomic Physics.

Instrumentation. Engineering Electronics. Electron Devices. Electronic Instrumentation. Mechanical Instruments. Basic Instrumentation.

Physical Chemistry. Thermochemistry. Surface Chemistry. Organic Chemistry. Molecular Spectroscopy. Molecular Kinetics. Mass Spectrometry.

Office of Weights and Measures.

BOULDER, COLO.

Cryogenic Engineering. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Cryogenic Technical Services.

Ionosphere Research and Propagation. Low Frequency and Very Low Frequency Research. Ionosphere Research. Prediction Services. Sun-Earth Relationships. Field Engineering. Radio Warning Services. Vertical Soundings Research.

Radio Propagation Engineering. Data Reduction Instrumentation. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Propagation-Terrain Effects. Radio-Meteorology. Lower Atmosphere Physics.

Radio Standards. High Frequency Electrical Standards. Radio Broadcast Service. Radio and Microwave Materials. Atomic Frequency and Time Interval Standards. Electronic Calibration Center. Millimeter-Wave Research. Microwave Circuit Standards.

Radio Systems. Applied Electromagnetic Theory. High Frequency and Very High Frequency Research. Modulation Research. Antenna Research. Navigation Systems.

Upper Atmosphere and Space Physics. Upper Atmosphere and Plasma Physics. Ionosphere and Exosphere Scatter. Airglow and Aurora. Ionospheric Radio Astronomy.

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